A New Design Approach for Road and Bridge Barriers

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Abstract

In Australia, the absence of standardised designs for bridge barriers and supports stems from the diverse array of bridge deck types, varying state regulations, and project-specific requirements. The expense and time involved in conducting crash tests mean they are not feasible for most cases. Consequently, designers must tailor barrier de-signs to each case. Typically, designers adhere to the load specifications outlined in AS5100, applying static loads and sizing members accordingly. However, this method overlooks the dynamic nature of these loads, resulting in inherently conservative designs. AS5100 also sets crash test criteria more stringent than AASHTO to accommodate heavier vehicles and higher speeds, yet the rationale behind these criteria lacks clarity.

Off-structure road barriers, in contrast, often follow standardised dimensions and support conditions based on extensive testing and documentation. Nevertheless, modifications may be necessary to meet specific safety requirements, with support conditions varying from standard cases. Similar to bridge barriers, crash tests are im-practical for road barriers, and guidelines for designing or assessing modified barriers are lacking. Some references to AS5100's static loads for bridge barriers are made, although the design principles between bridge and road barriers are substantially different.

This paper proposes alternative design approaches for barriers, departing from the conventional oversimplified and overly conservative methods. It advocates for modelling barrier performance under dynamic load pulses, offering a simpler approach suitable for common commercial programs. This method promises greater accuracy in capturing barrier behaviour and versatility for various applications, including both bridge barriers and off-structure road barriers.

1.0 Introduction

In Australia, there are no standard designs for bridge barriers and barrier supports. It is difficult to have standard designs as there are numerous bridge deck types. Each state and each project would also have different barrier requirements. Crash tests are too expensive and too time consuming. There is a current project by Austroads where load tests are carried out but the results are yet to be released (https://austroads.com.au/infrastructure/bridges/bridge-barrier-design)

As a result, designers would need to design barriers case by case. The common approach is to use the loads specified AS5100. These loads are applied as static loads and the member sizes are calculated accordingly. This method of design ignores the fact that the loads are dynamic in nature. The designs can therefore be inherently conservative.

AS5100 also specifies crash test criteria that are more stringent than AASHTO. This is to allow for heavier vehicles and higher speeds (Colosimo, 2014). It is not clear how these parameters were chosen and there were no studies on the traffic composition and the likelihood and the risk of these heave vehicles colliding with bridge barriers at full speed.

Off structure road barriers are however usually standardised. These have been tested and standard dimensions and support conditions are well documented. However, the standard barrier dimensions are often required to be modified to suit site constraints and/or certain safety requirements. The barrier support conditions, i.e. its foundation, can also vary from the standard cases. Similar to bridge barriers, it is often not practical to carry out crash tests for project works. There is, however, no clear guidance on designing or assessing these modified barriers. In some instances, references to the equivalent static loads in AS5100 for bridge barriers are made (DTP BTN???). Yet the design of bridge barriers and road barriers are usually significantly different. If a road barrier is designed using the conventional bridge barrier design approach, it would require significant additional reinforcement and supports. It can result in substantial cost increase given the road barrier lengths are often very long. For a large road project, the cost increase would be hundreds of million dollars.

This paper describes a design approach for barriers. These deviate from the conventional design approach which is oversimplified and over conservative. This involves modelling of barrier performance under dynamic load pulses. It is simple enough that can be used for design using common readily available commercial programs. It can capture the barrier behaviour more accurately and it can be versatile enough to be used for most common barrier applications including bridge barriers and off structure road barriers.

2.0 Barrier Collision Loading

Australian Standards adopt the loading from AASHTO. AASHTO 2020 Section 13 describes the methodology to analyse bridge traffic barriers and defines the primary purpose of barriers as to contain and redirect vehicles. This standard also specifies that new barrier systems can be designed by crash tests based on the test levels (Table 1).

Table 1: Test level crash test requirements from AASHTO

Vehicles	Imperial			Metric		
	Single unit van	Van type tractor trailer	Tractor Tankers Trailer	Single unit van	Van type tractor trailer	Tractor Tankers Trailer
Weight, W (kips/ton)	22	79.3	79.3	10.0	36.0	36.0
Wheel spacing, B (ft/m)	7.5	8	8	2.288	2.440	2.440
Height of centre of gravity, G (in, m)	63	73	81	1.600	1.854	2.057
Crash angle, theta (degree)	15	15	15	15	15	15
Speed (mph/kmh)						
TL-4	55			88.55		
TL-5		50			80.50	
TL-6			50			80.50

The standard also specifies the design loads in Table A13.2-1 that is reproduce below in Table 2. These loads were derived by Hirsch (NCHRP 86) and they were derived from a mathematical model as shown below. The equations presented in this document relate vehicle decelerations with entry speed, angle, vehicle dimensions and rail deflection. The impact forces are then derived using Newton's second law of motion. The equations were validated against California full scale test results by comparison of vehicle exit velocities and exit time interval and good matches were observed despite the fact that they are highly simplified. The equivalent total force, F, is calculated using the expression below.

$$F = \frac{1.25mv_I^2 sin^2\theta}{ALsin\theta - B(1 - cos\theta) + D}$$

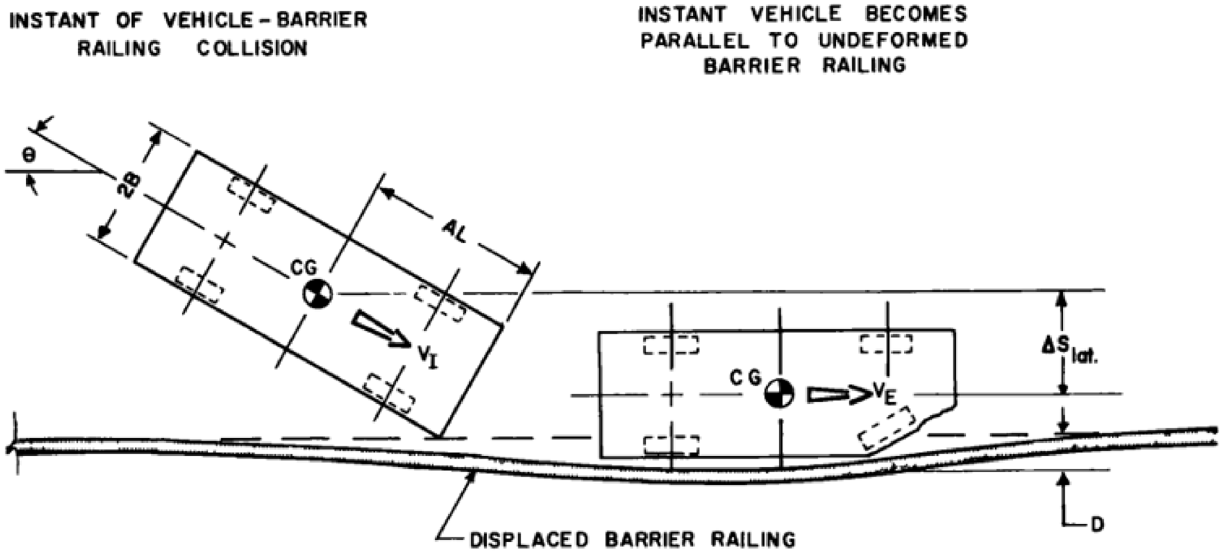


Figure 5. Mathematical model of vehicle-barrier railing collision.

Figure 1: Mathematical model of vehicle-barrier collision per NCHRP 86

Table 2: Design loads for crash test barriers

Design forces	Imperial			Metric		
	TL-4	TL-5	TL-6	TL-4	TL-5	TL-6
Transverse, Ft (kips/kN)	54	124	175	240	552	778
Longitudinal, FL (kips/kN)	18	41	58	80	182	258
Vertical, Fv (kips/kN)	18	80	80	80	356	356
Longitudinal length, Lt and LL (ft/m)	3.5	8	8	1	2	2
Longitudi-nal length, Lv (ft/m)	18	40	40	5	12	12
He (m)	32	42	56	0.81	1.07	1.42
Hmin (m)	32	42	90	0.81	1.07	2.29

The barrier collisions have also been studied by computer simulations (Sheikh et al, 2012). These highly sophisticated simulations can simulate how the vehicle interacts with the barriers throughout the impact (Figure 2). This is a well-documented method and can assess the barrier performance well. In the simulations, the applied loads can be plotted against time directly from the models. One example is shown below where the peak loads appear to last approximately 0.03 secs (Figure 3). However, it is still a time-consuming exercise and requires special skills and tools.

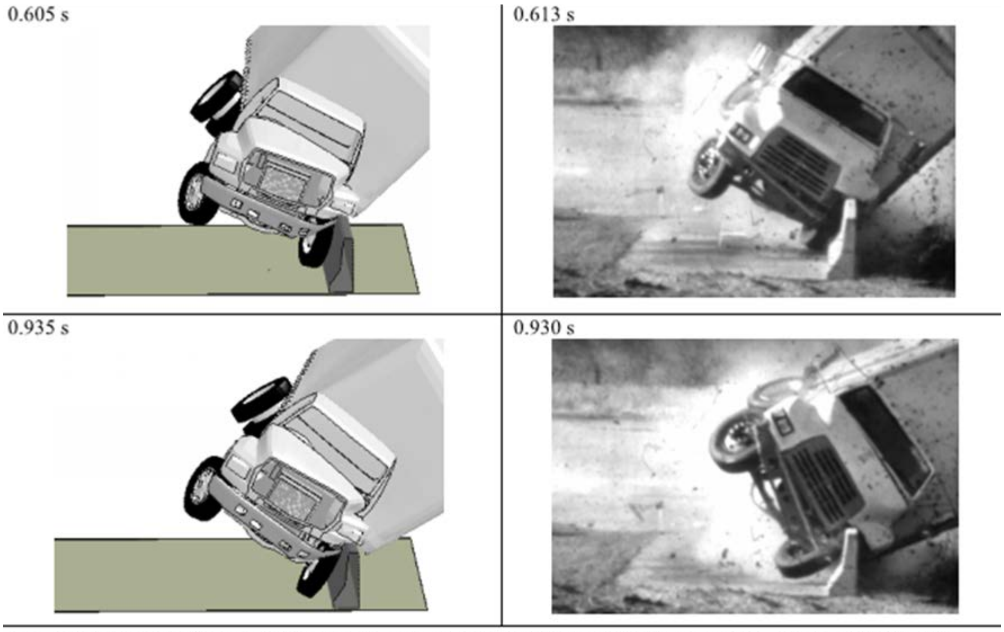


Figure 1 Comparison of simulation and crash test results for impact of SUT with 32-inch tall NJ barrier under MASH TL-4 impact conditions.

Figure 2: Comparison of simulation and crash test results (Sheikh et al. 2012)

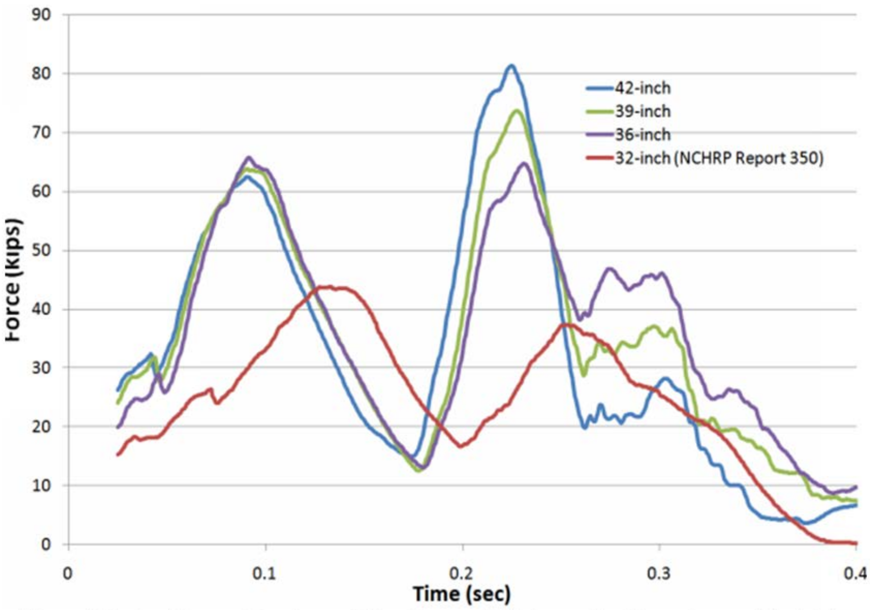


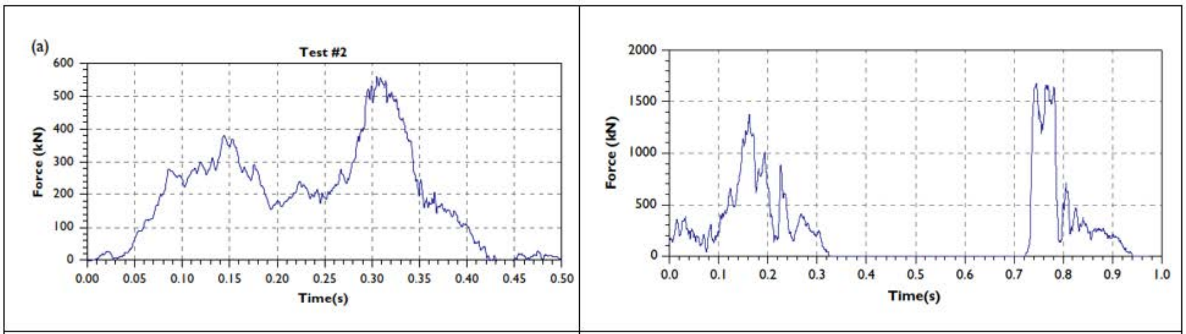
Figure 5 Lateral impact loads resulting from vehicle impact with various rail heights.

Figure 3: Lateral impact loads resulting from vehicle impact for MASH TL4 (Sheikh et al. 2012)

For design purposes, the forces on the barrier are often treated as static forces in the design but it is clear from the simulations that they are dynamic forces and would occur over a short duration. The material strain rate is also high in a collision and its effects on material strength and stiffness are significant. However, these effects are often ignored.

An alternative procedure to study barrier behaviour is to apply the load as a force versus time function. This was first recommended by Yong et al (2023). The force functions were derived by simplified computer simulation and crash test data by William et al (2018). The functions appear to be derived indirectly from the acceleration time-history and its peak forces appear to be higher than the forces calculated directly from full computer simulation. It is worth noting that the data are from collision of trucks on concrete barriers with a rigid base connection.

The force function typically has two peaks (Figure 4). Each pulse lasts approximately 0.2 to 0.3 seconds. The time gap between the peaks vary between 0.15 to 0.62 seconds.



a) TL-4 | b) TL-5

Figure 4: Contact force time-history derived by Yong et al, 2023

Yong et al (2023) also studied the influence of barrier stiffness on the peak contact force on barrier which clearly showed the significance of stiffness on the peak force. While the force stays relatively constant when the stiffness is high similar to that of a rigid performance barrier, the force reduces greatly as the barrier stiffness and its support stiffness reduce (Figure 5). For semi-rigid barriers similar to that of a test barrier, the peak force is approximately half of the peak force.

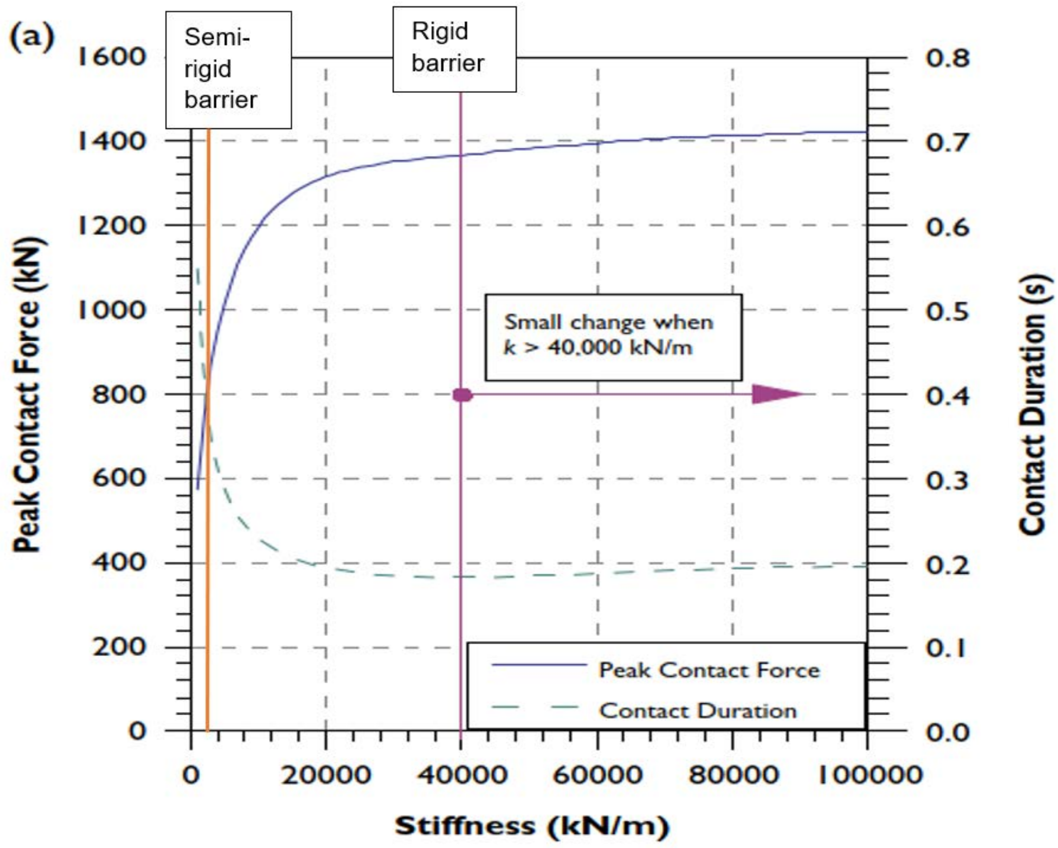


Figure 5: Effect of stiffness on peak force as predicted by Yong et al, 2023

From this study, it is proposed that road barrier capacities are determined for the loads applied as a force versus time function which consists of two pulses (Figure 6). For semi-rigid barriers such as concrete barriers without solid foundation or post-and-rail barriers, the peak loads are taken per AS5100 equivalent loads. For rigid concrete barriers on bridges, higher peaks are recommended. Based on Yong et al. study, the peak is taken to be twice the loads defined in AS5100. Other parameters such as pulse durations and pulse time gaps are proposed per Table 3. It is believed that the parameters would provide a safe design yet not too conservative.

The ability for barrier to fulfil its function is deemed adequate if it is stable under the applied loads and it does not deflect excessively. AS5100.2 Supplementary specifies a maximum rotation of 40 degrees for post and rail barriers. For concrete barriers, a maximum rotation of 20 degrees is proposed.

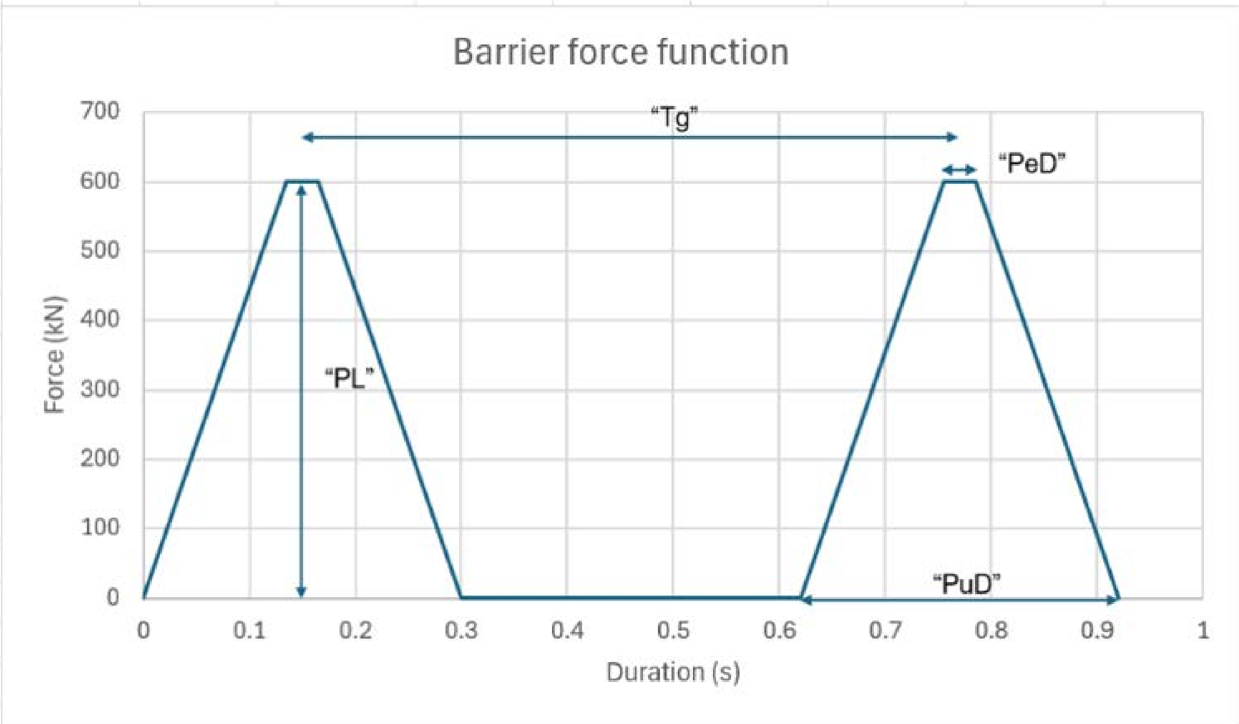


Figure 6: Barrier force function for a Semi-rigid TL-5 barrier

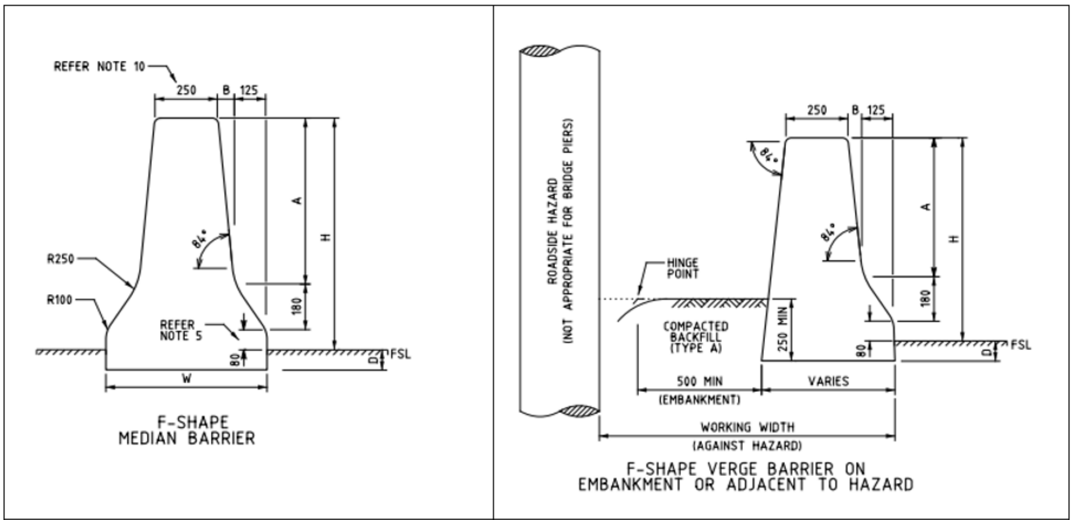
Table 3: Proposed force function for designing and assessment of barriers

Force function parameters	**Semi-reigid**			**Rigid**		
	TL-4 Regular Perfor-mance	TL-5 Medium Perfor-mance	TL-6 High perfor-mance	TL-4 Regular Perfor-mance	TL-5 Medium Perfor-mance	TL-6 High perfor-mance
Peak load (kN)	300	600	1200	600.0	1200.0	2400.0
Pulse duration (sec)	0.2	0.3	0.3	0.2	0.3	0.3
Peak duration (sec)	0.03	0.03	0.03	0.030	0.030	0.030
Minimum time gap (sec)	0.12	0.496	0.496	0.12	0.496	0.496
Maximum time gap (sec)	0.18	0.744	0.744	0.18	0.744	0.744

3.0 Assessment of Road Barriers

3.1 Road Safety Barriers in Victoria

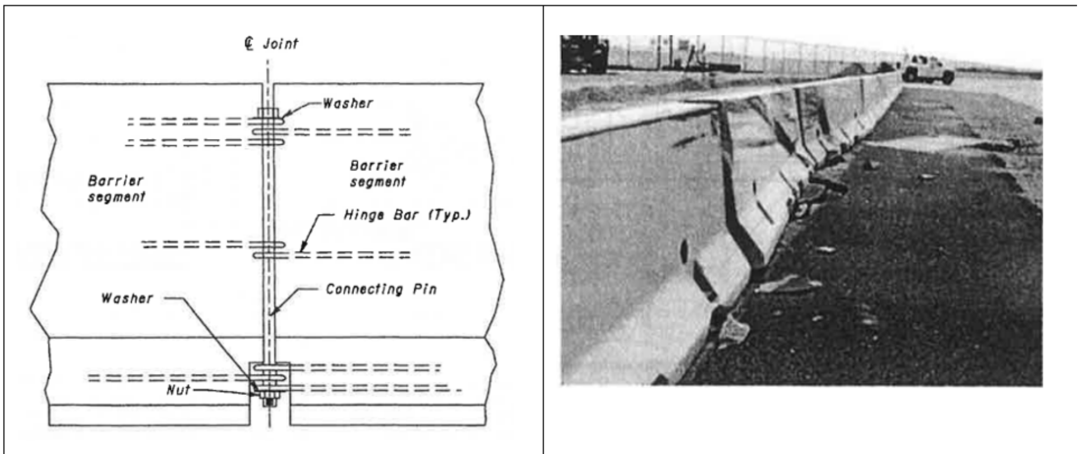
Concrete road barriers in Victoria Australia are typically of F-shape (Figure 6). The roadside barrier and median barrier profile are defined by Department of Transport for the state. These barriers can be precast or cast-insitu. The precast segments are typically connected such that they behave like a continuous barrier. These standard barrier sections have been tested and used for a long time (Figure 7).



a) F-shape median barrier

b) F-shape verge barrier

Figure 6: Road safety barrier profile defined by Department of Transport in Victoria



a) Typical pin and loop detail

b) TL3 test from McGinnis (2010)

Figure 7: Precast concrete barrier detail and photo (McGinnis, 2010)

It is worth noting that given the recent changes in ‘working width’, the road barrier section is often required to be modified. This modification is allowed by DTP but, recently, its Bridge Technical Note 001 requires that if the barrier height exceeds the standard height, it must be designed to resist loads per AS5100 applied at the top of the face of the barrier. If the conventional approach to design barriers to AS5100 is used for road barriers, a foundation would be required to TL-4 or higher performance level barriers. The foundation can be made of piles or friction slabs and they are often a significant cost item.

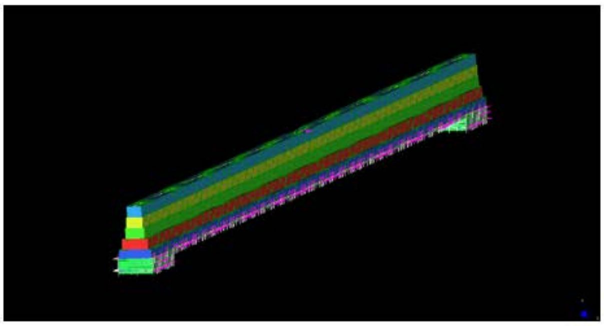
In this assessment, the approach as discussed in Section 2 is used where the loads are applied dynamically. While the load applies at a location along the barrier height, it is proposed there that the force function is applied at the top of the barrier. This transient analysis can be carried out relatively easily using commercial software such as Strand7.

It is also worth noting that AS5100 permits the use of nonlinear finite element analysis or rigorous structural analysis. The approach as described below is compliant with this standard.

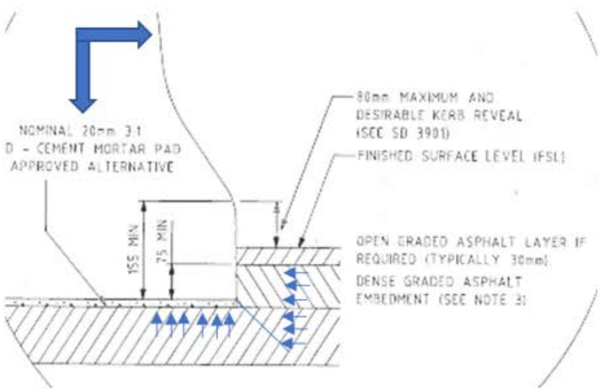
3.2 Nonlinear Transient Models

A range of modified road barriers were considered in this assessment. They include 920mm, 1320mm and 1500mm high TL-4 barriers, and 1100mm, 1320mm and 1500mm TL-5 barriers. It is believed that rather than providing a rigid foundation, the embedment depth can be increased to account for the increased in height.

The concrete parapet is modelled using shell elements with the restraints from asphalts and subbase modelled using “Winkler Springs” (Figure 8). A full-length barrier was modelled (48m for TL-4 barriers and 66m for TL-5 barriers) with end anchorages included.



a) Strand7 model of road barrier



b) Restraints from pavement and subgrade

Figure 8: Modelling of road barriers

The material strengths used in the model are as below. Concrete strength was taken as 32MPa.It was found that the critical mode is overall stability of the barrier rather its strength. Therefore, concrete is modelled as a linear elastic material.

The load pulses are applied on the barrier per Section 2 for semi-rigid barriers.

3.3 Pavement Properties and Modelling of Restraints

The stability of the barrier depends a great deal on the stiffness and strength of the asphalt layer that the barrier is keyed in. Asphalt is typically a mixture of aggregate and bitumen which is spread and compacted while hot. The strength and elasticity of asphalt is derived from a combination of friction between aggregate particles and the viscosity and cohesion of the bitumen. As a result, the strength and elasticity of asphalt is dependent on a multitude of factors including particle angularity, compaction density, bitumen type, bitumen content, age, extent of cracking, temperature, direction and rate of loading and degree of strain.

VicRoads (2018) presents characteristic modulus values of 1000MPa to 1800MPa (1200MPa typical) for dense graded asphalts at a weighted mean annual pavement temperature of 24 degree C (appropriate for Melbourne) and at traffic speeds of 10km/h. With increased rate of loading (i.e. at design speeds of 60km/h) modulus values increase to about 1500MPa to 3100MPa (2000MPa typical). It is noted that these characteristic modulus values are based on the resilient strain measured in the laboratory in accordance with Australian Standard AS1289.13.1 and are specifically used for the design of pavements. In this laboratory test horizontal microstrains of 30 to 70 are generated in a cylindrical sample by the application of a series of vertical compressive force pulses. The modulus is then calculated based on the resilient or total recoverable strain recorded in the test (i.e. the peak strain recorded in the test minus the strain immediately prior to the application of the next load pulse).

The modulus of the asphalt under the loading rate and strains generated by a crash load on the barriers would be expected to differ from the modulus measured in accordance with AS1289.13.1 for use in pavement design.

Neither VicRoads (2018) nor AustRoads AGPT04/07 provide any guidance on the shear strength characteristics of asphalt as within the strains generated by road traffic, asphalt behaviour is considered linear elastic and as such only the elasticity parameters are considered in design. Mattos et al (2016) undertook a literature review of triaxial test results on conventional asphalt and modified asphalts as part of their study into near surface pavement failures in Brazil. They quoted a friction angle of 45 degrees and a cohesion of 600kPa at 25 degree Celsius. Nunez et al, based on the results of triaxial tests, reported a friction angle of 46 degrees and a cohesion of 480kPa at the same temperature. Bindu and Beena (2013) undertook triaxial testing on 'stone matrix asphalt' with various additives and reported a friction angle of 35 degree and a cohesion of 110kPa when tested under confining stresses of 0 to 100kPa at a temperature of 60 degree C with deviator loads applied at a rate of 50.8mm/min.

As noted by Bindu and Beena, the cohesion increases with increasing loading speed and as such the test results would represent a lower bound estimate of cohesion expected under traffic. The rate of loading under a crash load would be significantly greater than that applied in the test scenario. The shear strength would also increase at reduced temperatures.

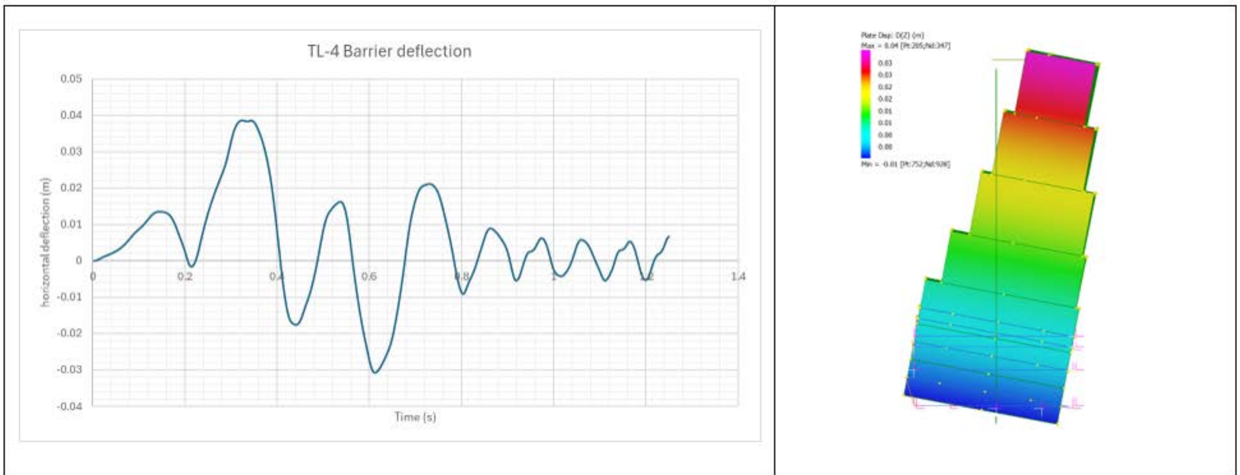
Based on these studies, a geotechnical model was used, and the subgrade reaction values were derived and are tabulated in Table 4 below.

	Lateral Spring Modulus	**Ultimate Lateral Spring Capacity**
Ashphalt	2×10^{7} kPa/m	2000 kPa
Crushed Rock	8×10^{5} kPa/m	100 kPa
Insitu Clay Soil	8×10^{5} kPa/m	220 kPa

Table 4: Pavement properties

3.4 Analysis Results

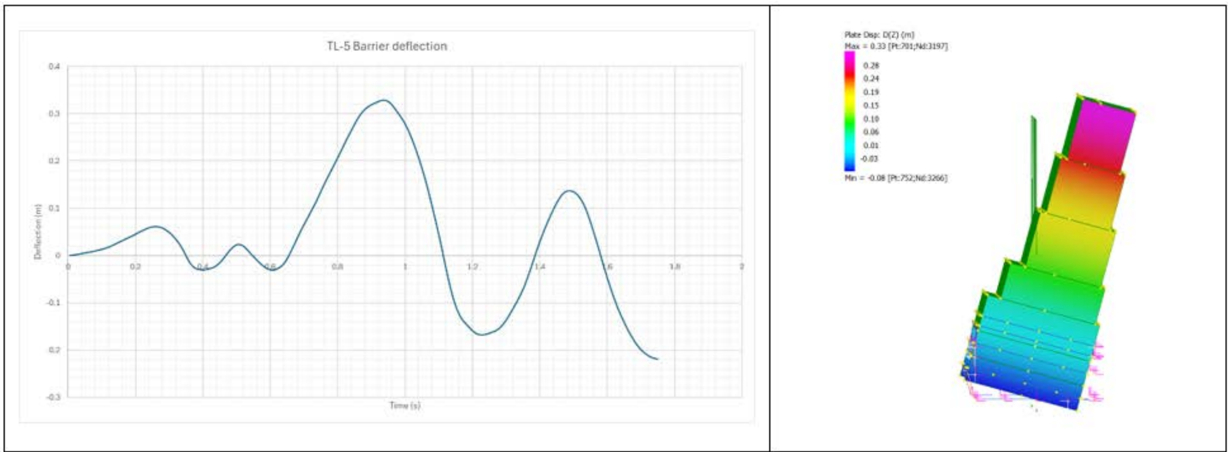
The base cases studied were 920mm TL-4 and the 1100mm TL-5 side barriers per DTP standard drawings. The parameters for the force function were determined to give the highest deflection for the barriers. The maximum deflections were with the limits (that are 315 and 375 mm for TL-4 and TL-5, respectively) suggesting that the standard barriers are sufficient to withstand the applied load, as expected (Figures 9 and 10).



a) Deflection vs time plot

b) Barrier rotation (magnified by 5x)

Figure 9: Deflection of a 920mm TL-4 barrier with 75mm embedment depth



a) Deflection vs time plot	b) Barrier rotation (magnified by 5x)

Figure 10: Deflection of a 1100mm TL-5 barrier with 100mm embedment depth

To determine the requirement embedment depth for the road barriers that have been modified, a series of models using the same approach as above were produced. The stability of the barrier was assessed, and the maximum deflections were checked. From these assessments, the following recommendations are provided for the modified barriers.

TL4 with 1320 and 1500mm heights: Increase embedment from 75 to 100mm.

TL5 with 1320 heights: Increase embedment from 100 to 200mm.

TL5 with 1500 heights: Increase embedment from 100 to 300mm.

The anchor block depth will increase by the same amount (from 250mm depth).

4.0 Bridge Barriers

4.1 Background

Bridge barriers within Victoria are required to be either semi rigid or rigid barriers as stated in DTP BTN001 with only the latter may be used for medium performance barriers or greater. The barrier forms used on bridge structures can be typically divided into three sets, concrete barriers, steel barriers, and concrete and steel barriers.

Concrete bridge barriers are required to have the standard F-shape profile while steel barriers must comprise of standard square or rectangular hollow sections only. Combined concrete and steel barriers require at least 900mm of concrete section to be above the FSL and may only be adopted for medium performance level or higher.

Bridge barriers are often designed in accordance with AS5100 where equivalent loads are applied as static loads. For full discrete concrete barriers, the barrier capacity is controlled by the stitch capacity. The bridge deck slab thickness is also controlled by barrier collision loads for this case. For continuous concrete barriers, local failure of barrier can control the design (Figure 14).

a) Precast discrete barrier failure (Hood Canal Bridge)

b) Continuous barrier failure (a Melbourne bridge)

Figure 14: Failure of bridge concrete barriers

4.2 Bridge Barrier Modelling

To investigate the use dynamic load method in the design of this bridge, a 40m span concrete bridge was modelled using the commercial software Strand7 (Figure 15). The superstructure comprises of 4 No. 1.85m deep Super T girders, a 200mm thick concrete deck. The girders are supported by elastomeric bearings atop a cantilever crosshead and pier column. The barriers are 1200mm high TL5 barriers. The concrete barriers were modelled as 7 separate barrier segments. The reinforcement in the stitch is N20-150mm. The barrier is compliant to AASHTO specification and AS5100 and they have been designed to minimize the loads on the deck.

A moment-curvature graph was generated for the barriers and applied to the stitch to allow for yielding of the stitch member. This is as per AS5100 which requires the bridge deck to have 110% of the barrier stitch strength.

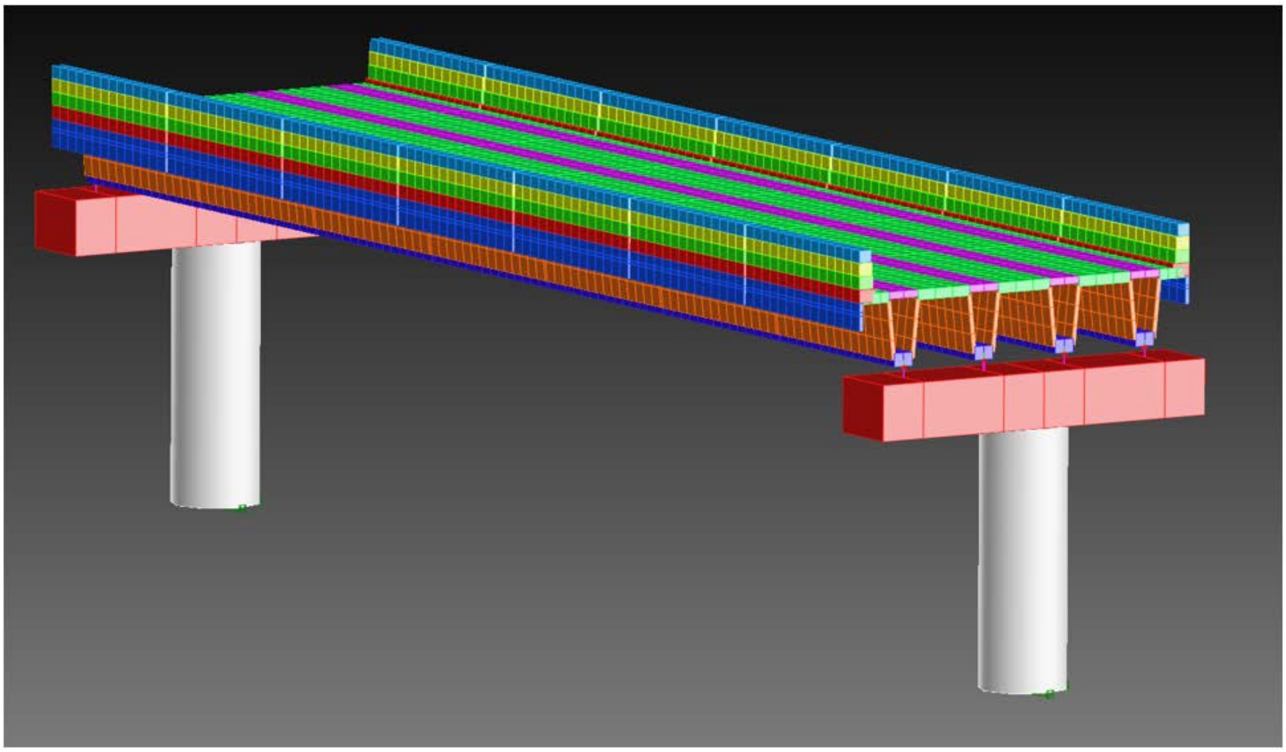


Figure 15: Strand7 model

To compare with the conventional method, we initially applied a static load of 600kN over a 2.4m length, consistent with AS5100.2 standards. Subsequently, we conducted a transient analysis using the discussed force function, applying it along a 2.4m barrier length.

In comparison to the static approach, the analysis indicated no improvement in the actions within the rigid concrete barrier and the adjacent deck. This lack of improvement can be attributed to the high stiffness of these elements. Therefore, for such components, the static load design approach remains recommended. However, actions in structural elements further away from the point of contact, such as at bearing levels and in the pier column, exhibited lower values compared to those derived from the static analysis. This suggests that for designing elements like bearing restraints and piers, utilizing dynamic loads could offer greater advantages.

5.0 Summary

The paper introduces a novel design methodology for barriers, centred on evaluating their performance under dynamic load pulses. Load functions were derived through a comprehensive literature review, and analyses were conducted utilizing commercially available software, Strand7. This design approach was employed to assess non-standard test barriers, aiming to determine their necessary embedment lengths. The findings revealed that costly rigid barriers are unnecessary for these applications. Additionally, the approach was applied to evaluate the performance of a barrier on a typical super T bridge, underscoring its advantages for designing various bridge elements.

6.0 References

AASHTO LRFD (2007) Bridge Design Specifications - Section 13

Atahan, Ali O., Marten Hiekmann, J., Himpe J. & Marra, J. (2017) Development of a continuous motorcycle protection barrier system using computer simulation and full-scale crash testing, Accident Analysis & Prevention

Athan, Ali O. (2005) Impact analysis of a vertical flared back bridge rail-to- guardrail transition structure using simulation. Finite Elements in Analysis and Design. Volume 41, Issue 4, pg 371-396

AS5100 (2017) Bridge Design Code

Bindu C.S. and Beena K.S. (2013) 'Comparison of Shear Strength Characteristics of Stone Matrix Asphalt Mixture with Waste Plastics and Polypropylene', in The International Journal of Structural and Civil Engineering Research, ISSN 2319, Vo. 2, No. 4

Department of Transport (2024) Standard Drawings

Marra, J., Cortese, M., Hansen, P. & Hansen D. (2017) Bridge anti-falling load systems performance qualification procedure proposal

Marzougui, D., Kan, C.D., and Opiela, K.S. (2014) Crash test & simulation comparisons of a pickup truck & a small car oblique impacts into a concrete barrier, Centre for collision safety and analysis – George Mason University

Mattos J. R., Nunez W. P., Ceratti J. A., Zingano A. and Fedrigo W. (2016), 'Shear strength of hotmix asphalt and its relation to near surface pavement failure – A case study in southern Brazil' Proceedings of the 6th Eurasphalt and Eurobitume Congress, Prague, Czech Republic

McGinnis R. G. (2010) Systhesis of crash tested precast concrete barrier designs and anchoring system - AASHTO

NCHRP 86

Se-Jin Jeon, Myoung-Sung Choi, and Young-Jin Kim, (2008) Ultimate strength of concrete barrier by yield line theory, International Journal of Concrete Structures and Materials Vol 2, No. 1, pp. 57-62

Standards Australia (2004) AS5100.2 Bridge Design - Design loads, Standards Australia, GPO Box 476, Sydney, NSW

Yong A. C. Y, Lam N.T.K, and Menegon S. J. (2023) Collision actions on structures CRS Press

VicRoads, (2005) Bridge Technical Note: Bridge Traffic Barrier Performance Levels and Design Loads - BTN 2005/006

VicRoads (2012) Bridge Technical Note: Bonded anchors - BTN 2012/002

VicRoads (2018) Code of Practice for Selection and Design of Pavements and Surfacings (RC500.22)

7.0 Author Biographies

Dr. Binh Pham serves as a Technical Principal at SMEC Australia. He has over 24 years of experience in structural design and design management across projects in Australia, the Middle East, and Southeast Asia. Binh has research and teaching skills. He is a specialist in strengthening structures using fibre-reinforced polymers and in advanced modelling of concrete and steel structures. Dr Pham has contributed to over 25 publications, served as a guest lecturer at universities, and is a recognised reviewer for international journals.

Basim Matar is a structural at SMEC Australia. Since joining the industry Basim has become adept at the use of finite element analysis. He has used these skills to assist in the modelling of complex structural interactions over various projects in Australia.

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